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Properties of a thermal-insulating wall material based on hemp shives and lime binder

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Abstract. The use of low-processed materials is a requirement for building in accordance with sustainable development. The examples of such materials are the components of plant origin – cellulose fibers, cereal straw and hemp/flax shives. Their carbon footprint is often negative since they absorb large amounts of carbon dioxide from the atmosphere during the plant growth. These materials are employed for thermal insulation or as a material for walls. Recently, hemp shives have enjoyed growing popularity in the production of lime-based composite, used for filling walls in timber frames. Owing to high porosity, the shives improve the thermal insulation properties characterizing the composite. By changing certain parameters, for instance the hemp shives to binder ratio, it is possible to modify the physico-mechanical properties of a composite; in contrast, the properties characterizing the hydrated lime binder can be altered using additives. The paper presents mechanical properties (compressive strength) as well as physical properties (density, porosity, thermal conductivity coefficient, absorptivity) of composites with various proportions of hemp shives of the Bialobrzeskie variety to the lime binder modified with gypsum and metakaolinite.

INTRODUCTION

Thermal insulation materials reduce the heat loss and thus the energy consumption in the use phase of the building [1]. However, their production and utilization are often energy-intensive (for example expanded polystyrene or mineral wool) and this results in a high embodied energy and high global warming potential of these materials [2-5]. Thermal insulation materials consisting of the materials of plant origin are characterized by lower embodied energy [6]. Their carbon footprint is often negative since they absorb large amounts of carbon dioxide from the atmosphere during the plant growth. Thermal insulation materials such as hemp wool, flax wool or straw bales are produced from such plants as industrial hemp, flax, wheat and rye. They are also used for the production of wall composites, performing a thermal insulation function and filling a timber frame structure. An example is cereal straw, which together with the clay binder forms a wall composite with an apparent density of 241-531 kg/m^3 and thermal conductivity of 0.071-0.120 W/(m·K) [7]. On the other hand, the woody parts of the hemp stalks, called the shives, together with the modified lime binder form a monolithic wall material, which is characterized by satisfactory thermal insulation properties (λ values in the range of 0.082-0.151 W/(m·K) [8]) and low vapor diffusion resistance coefficient in the range of 5-6 [9]. The properties of this material depend on the ingredients used, as well as on the method of preparation (compaction). Besides shives, hemp fiber is also used as thermal insulation (λ value about 0.4 W/(m·K) [10]). During growth, hemp is capable of absorbing significant amounts of CO_2: 1 ton of hemp shives can store 1.8 tons of carbon dioxide, while 1 m^3 of hemp-lime composite is able to store approximately 110 kg of CO_2 [11]. In order to minimize the environmental impact of the composite, local hemp

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yields and local binder constituents are used, which is why various compositional recipes are tested, containing, (in addition to hydrated lime): hydraulic lime [12], cement [13], MgO cement [14] or zeolite [14].

The study focuses on the applicability of local renewable materials obtained from agriculture in the construction industry, e.g. hemp shives with lime binder. The paper presents the physical (porosity, density, absorptivity, thermal conductivity coefficient) and mechanical properties (compressive strength) of ecological composites with different bio aggregate (hemp shives) to lime binder ratios with gypsum and metakaolinite additions.

MATERIALS

The research was conducted on an ecological composite based on modified lime binder and bio aggregate in the form of hemp shives, obtained from the Białobrzeskie variety of industrial hemp. The shives obtained from this variety of hemp were used in other studies, but in different fractions, usually longer and more varied [8, 13, 15]. Four mixes of different proportions of the applied compounds were investigated. They differed in the proportion of filler to binder. The weight proportions were used: 1: 1.4, 1: 1.5, 1: 1.6 and 1: 1.7. The recipes are marked with symbols HL1.4 - HL1.7. The composite recipes are shown in Tables 1 and 2.

TABLE 1. Compositions of composites

Composite	Filler : binder weight ratio	Binder : water weight ratio
HL1.4	1 : 1.4	2.31
HL1.5	1 : 1.5	2.45
HL1.6	1 : 1.6	2.56
HL1.7	1 : 1.7	2.67

TABLE 2. Recipes of composites (the percentage of binder and filler components)

Composite	Binder components [%]			Filler components [%]
	Hydrated lime	Gypsum	Metakaolinite	Hemp shives
All recipes	75	15	10	100

The length of the applied hemp shives was about 5-25 mm. They were purified from the dust and excessive amount of fibers. The bulk density of hemp shives in loose form is about 100-120 kg/m^3 and the thermal conductivity coefficient, according to the literature, is about 0.052-0.062 W/(m·K) [16]. They are also characterized by a high porosity (about 80%) and high mass absorptivity (about 400% dry weight after 48 h of soaking). The hemp shives used in our studies are shown in Figure 1.

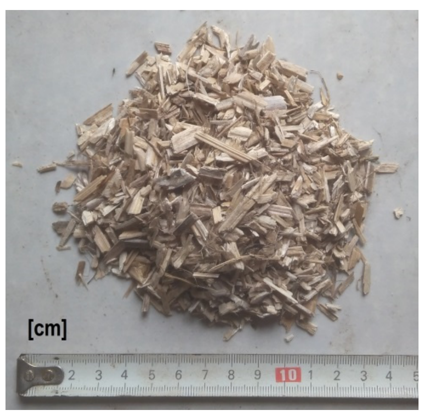

FIGURE 1. Hemp shives used in studies

The same binder was used in all of the applied recipes. It consisted of hydrated lime CL-90s (75% of binder dry mass) with gypsum (15% of binder dry mass) and pozzolanic addition – metakaoline (10% of binder dry mass). Hydrated lime, due to its high water vapor permeability and high pH, is a suitable binder in combination with organic fillers. Gypsum was added to accelerate the binding process and metakaolinite was added to increase the strength and improve the water resistance of composites.

METHODS

All of the samples used in investigation were maturating under laboratory conditions (air temperature 20 °C±2 °C, air relative humidity 55%±5%) for 28 days after preparation.

The apparent density and porosity tests were carried out according to EN 12390-7:2001 standard on three cubic specimens of dimensions 100×100×100 mm from each recipe. The specimens of known volume were dried to constant mass, and the apparent density was calculated after weighing them. The specific density of the hemp-lime composites was determined by means of the pycnometric method in accordance with EN 1936:2010. Total porosity was estimated as a ratio of total volume of open and closed pores per sample volume. It was calculated based on the determined specific density values.

The mass absorptivity test was investigated in accordance with EN 13755:2002 standard on three specimens from each recipe, with the dimensions of 100×100×100 mm. The test consisted in controlling an increase in mass of the samples immersed in water until the state of total saturation occurred. The specimens were soaked in water for about 7 days.

The thermal conductivity test was performed on three specimens from each recipe with the dimensions of 300×300×50 mm. The thermal conductivity study was implemented on the basis of international standard ISO 8302 method. The study was set up in the plate apparatus Laser Comp Fox 314, the heat flow meter method. Before the test, the samples were dried to constant mass in an oven at 60 °C. During the thermal conductivity test, the temperature set on a hot plate was 25 °C, while the cooling plate was 0 °C, and the obtained average temperature equaled 12.5 °C. The absolute thermal conductivity accuracy of the plate apparatus FOX 314 was ±2%.

The compressive strength was determined after 28 days of maturation on three samples with the dimensions of 150×150×150 mm, from each recipe, using a hydraulic press with a load range of 0÷250 kN. In this study the press head was controlled by the displacements with a value of 5 mm/min. The loads and displacements were measured.

RESULTS AND DISCUSSION

Apparent density, specific density and porosity

The apparent density of the tested composites ranged between 397.7 and 419.5 kg/m^3 (Table 3). On the basis of the results, it can be noted that the apparent density increases with increasing the binder content in the mix. This phenomemon is confirmed in the literature [8, 15]. The power and method of compacting the mixture also influence the density of the composite [17]. However, the volume of the composite is not affected by a greater lime binder quantity (used in the investigation), since it only fills the voids between hemp shives.

The investigated hemp-lime composites had the total porosity ranging from 79.8 to 80.5% (Table 3). This parameter remains high in every composite, owing to a large share of porous filler components as well as the composite preparation technique in which various lengths of hemp shives air voids appear among particles in the course of the compaction process. Another test [18] showed that the composite was characterized by total porosity reaching 79%, while the apparent densities ranged from 430 to 460 kg/m^3.

TABLE 3. Apparent density, specific density and total porosity of tested composites

Composite	Apparent density [kg/m^3]	Specific density [kg/m^3]	Total porosity [%]
HL1.4	397.7	2039.5	80.5
HL1.5	407.7	2059.1	80.2
HL1.6	414.6	2083.4	80.1
HL1.7	419.5	2076.7	79.8

Mass Absorptivity

Mass absorptivity of the tested composites after 7 days of immersion in water is shown in Figure 2.

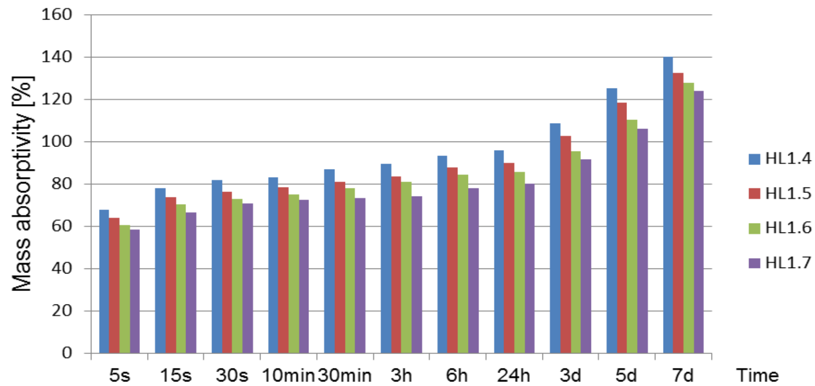

FIGURE 2. Mass absorptivity of tested composites over time

The investigated composites are characterized by mass absorptivity of 111.2-138.2%. Absorptivity is reduced when the lime binder content is increased, due to the sealing of the shives surface. All the considered composites exhibit high water absorption, resulting from the large share of hygroscopic organic fillers and their high total porosity. The absorptivity increased the most in the first few seconds following submersion of the composites in water, reaching 58.7-67.9% after the first 5 seconds. Hence, it is essential to protect the composite against even short contact with water.

Thermal conductivity

The results of the thermal conductivity test are shown in Figure 3. Error bars mean confidence intervals for the average.

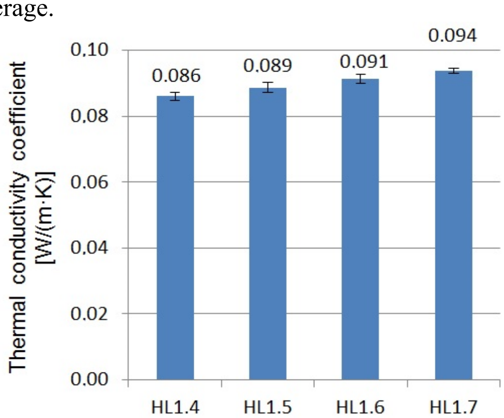

FIGURE 3. Thermal conductivity coefficient of composites

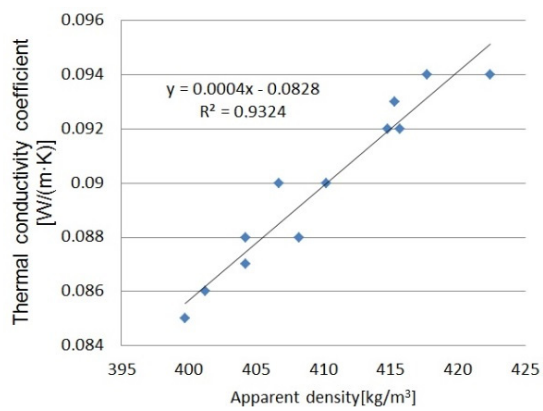

FIGURE 4. Relationship between thermal conductivity and apparent density of hemp-lime composites

The hemp-lime composites are characterized by the thermal conductivity coefficient in the range of 0.086-0.094 W/(m·K). The thermal conductivity is closely related to the porosity of the material [8]. The λ coefficient of the composite increases along with the binder content, which is confirmed by other studies [8, 13, 16]. The composite porosity, and hence the quantity of air trapped in its structure, are reduced by increasing the amount of binder content. Thermal conductivity of the lime binder is about 0.7 W/(m·K), while λ of hemp shives are definitely lower [16].

The density of the material governs the thermal conductivity coefficient λ value characterizing the hemp-lime composite. It is dependent on the binder to filler ratio as well as the mixture preparation method (laying and compacting). This dependence is also true for other building composites [19]. As indicated in the own research and the literature, the conductivity coefficient is increased along with the apparent density of composites. Figure 4 presents the relationship between the thermal conductivity of a composite and its apparent density. Thus relationship can be considered linear; the obtained coefficient of determination (R^2) for the considered composites amounts to 0.9324.

Compressive strength

The results of the compressive strength test of composites are shown in Figure 5. Error bars mean confidence intervals for the average.

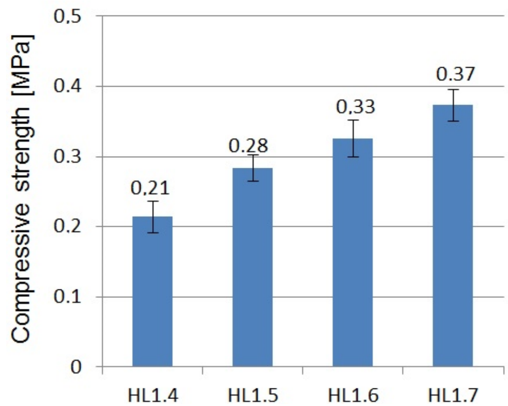

FIGURE 5. Compressive strength of tested composites

The composites are characterized by the compressive strength ranging from 0.21 to 0.37 MPa. Similar strength values were obtained in other studies [15] for hemp-lime composites with apparent density of 404.4-483.5 kg/m^3, but containing other binder (Portland cement instead of gypsum) and longer fraction of shives. The literature indicates that the strength parameters are governed by the binder type, binder to filler ratio, share of shives and the mixture compaction technique [8, 9, 20]. In this research, the compressive strength increases along with the binder amount. The obtained results are uniform. The quantity of binder and hemp shives has an influence on the strength parameter. The hemp shives, especially in the case of longer fibers and fractions, provide micro-reinforcement of the composite. The form of deformation obtained in the course and after the load test was dependent on the shives.

Fig. 6 presents the relationship between load and displacement obtained in the course of the compressive strength test. In the first phase, the material exhibits elastic behavior. The binder holding non-compressed hemp shives plays the main role at this stage. When the binder is destroyed, deformation increases with a slight raise in the load. When the load is at maximum, the bond between the binder and shives is completely damaged. The composite sample loses its strength and deformations are aggravated. With the destructive load applied, the displacement of the sample reached about 14-15 mm. Fig. 7 shows the form of destruction of an exemplary sample in which the displacement amounted to 20 mm.

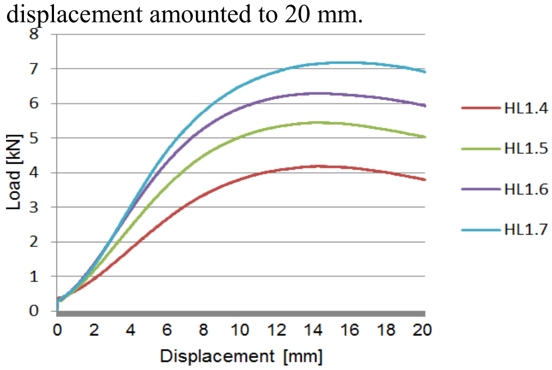

FIGURE 6. Relationship between load and displacement during compressive strength test of composites

FIGURE 7. The form of destruction of an exemplary composite sample after a compression test

CONCLUSIONS

The paper presents the results of research and own observations on the properties of ecological composites consisting of binder (based on lime) and bio aggregate filler in the form of hemp shives. It was shown that the material is characterized by low apparent density (397.7-419.5 kg/m^3) and low thermal conductivity (0.086-0.094 W/(m·K)) caused by a high total porosity (79.7÷80.5%). High porosity also determined the high absorptivity, which reached 58.7 to 67.9% after only 5 seconds of immersion in water. The composites have low compressive strength, in the range of 0.21-0.37 MPa, but they are not designed as load bearing materials. Together with the increase of binder content in the composite, its apparent density, compressive strength improved as well, whereas the total porosity, absorbability and heat conduction decreased.

The research shows that it is possible to use local hemp shives and modify the binder using local ingredients (e.g. gypsum) without significant differences in the properties of the composite, comparing the results to the literature.

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